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Numerical Simulation of Bridge Response Under A Moving Downburst: Parameter Optimization Using Surrogate Model

Jianming Hao [1,*], Lingfeng Xin[1], Yu Feng [1], Jiawu Li[1], Teng Wu [2]

[1]School of Highway, Chang' an University, Xi'an, China, jianminghao@chd.edu.cn (J. Hao); 2021221036@chd.edu.cn (L. Xin); rainingfeng@chd.edu.cn (Y. Feng); ljw@gl.chd.edu.cn (J. Li)
[2] Department of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY, 14260, USA, tengwu@buffalo.edu (T. Wu)

SUMMARY:
Assessment of bridge performance under a thunderstorm outflow requires accurate simulation of moving downburst. The impinging jet model with sliding mesh technology was introduced to simulate the moving downburst, and the variation of the wind field during the movement of downburst was investigated. To make simulation results fit well with measurements, a parameter optimization method was developed. The target wind speed time history was selected into several feature points, and the objective function was established based on the errors between the simulated characteristic points and the target values. To increase effectiveness, a Kriging surrogate model that was trained using data from numerical simulation was used. The parameter optimization method and the Kriging model were verified using five groups of test samples. The results demonstrated the significance of the relative values of the jet velocity U_j, moving velocity U_T and ambient wind speed U_b to the time-varying mean wind speed of the downburst. The parameter optimization efficiency was significantly increased by replacing the numerical model of computational fluid dynamics (CFD) with a surrogate model during optimization iteration. The simulation accuracy was clearly improved by the numerical modelling of a downburst based on optimized parameters. Finally, the dynamic response of a long-span bridge subjected to the moving downburst was presented.

Keywords: parameter optimization, moving downburst, long-span bridge

1. INTRODUCTION

Field measurements are one of the effective methods to study the downburst flow field characteristics. NIMROD and JAWS programs have been carried out in the U.S. (Fujita, 1981; Hjelmfelt, 1988), which have provided valuable data for the study of downburst wind field characteristics. However, due to the temporal contingency and spatial randomness of downburst flow occurrence, there are difficulties in field measurements. Therefore, experimental/numerical simulations following the formation mechanism of downburst storms have become an alternative solution to study the wind field characteristics of downburst during a thunderstorm. The cold source sub-cloud model (Anderson et al., 1992) and impinging jet model (Fujita, 1958) are mainly utilized for downburst simulation. Since the flow characteristics and wind-induced structural response of wind fields are the focus of attention in the field of structural wind engineering, impinging jet models with high simulation accuracy in the near-surface region have been widely used in the simulation of downburst wind fields.

Since there are fundamental differences between the impinging jet model and the formation mechanism of the real downburst wind, it is not easy to achieve good match between the simulation of downburst wind and the measured data collected in the field. Currently, effective mapping relationship between the simulated parameters and the wind observation data is not established yet. This study employs a grid slip technique to simulate moving downburst flow based on the impinging jet model of computational fluid dynamics (CFD). Then it proposes a parameter optimization method for downburst flow simulation based on Kriging model, verifies the accuracy of Kriging model and the effectiveness of the parameter optimization method through five sets of test cases. Finally, the dynamic response of a long-span bridge subjected to the downburst is calculated.

2. NUMERICAL SIMULATION OF MOVING DOWNBURST

A three-dimensional impinging jet model is used for the numerical simulation of the moving downburst, as shown in Fig. 1. The downstream jet impacts the ground from the velocity inlet and spreads outward after making contact with it, with the peak wind speed forming close to the ground. The jet inlet is a circle with diameter D_j, and placed at the computational domain with the height $2D_j$ from the ground. The downstream jet diameter for typical downburst events is approximately 1000 m, and the numerical model in this study adopts a geometric scaling ratio of 1:1000, thus taken D_j=1. Considering the spatial symmetry characteristics of the downburst wind field, the rectangular computational domain is chosen and symmetric boundary conditions are introduced in the numerical model. The SIMPLIC solver and SST $k-\omega$ turbulence model are adopted for calculation. The settings of the boundary conditions of the computational domain are demonstrated in the Fig. 1. In order to realize the spatial movement of the downburst, the grid slip technique is introduced in the moving downburst simulation (Hao and Wu, 2018).

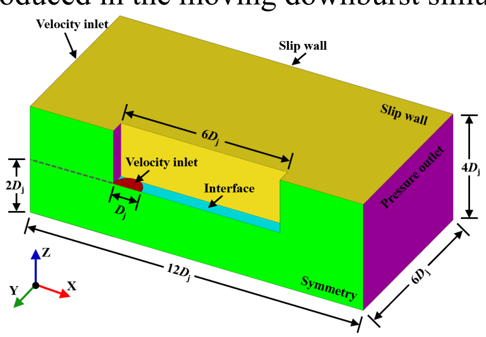


Fig.1 Numerical Model and Mesh of Moving Downburst

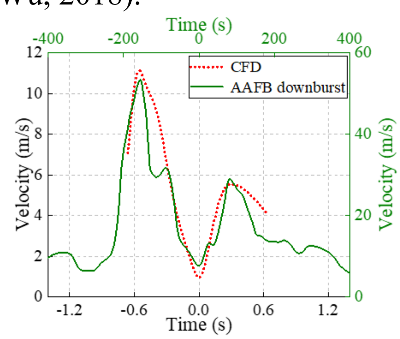


Fig.2 Comparison between AAFB Downburst and Simulation

The numerical wind speed time-history of point P (0,0,0.05$\boldsymbol{D_j}$) during the downburst movement is shown in Fig. 2, while the measured data of AAFB downburst are also plotted in the figure. Considering the differences in velocity and time scales between the numerical simulation results and the measured data, two sets of time and velocity coordinates are used in the figure for comparison. From the figure, it can be found that the overall time-varying trend of the numerical simulation results is basically consistent with the measured data, reproducing the typical characteristics of the double velocity peak of the measured data. However, for a specified velocity/time scaling ratio, the velocity peaks and valleys of the numerically simulated time-history and their moments of occurrence show obvious deviations from the measured values, which may be the result of estimation errors in the simulation parameters. As a result, the simulation parameters must be adjusted to reduce the errors in the simulation results.

3. OPTIMIZATION OF SIMULATION PARAMETERS BASED ON KRIGING SURROGATE MODEL

3.1. Optimization Strategy

Figure 3 shows the optimization process of downburst simulation parameters. Firstly, the initial values of the simulation parameters are set; then, the numerical simulation of the downburst is performed and the objective function is constructed; finally, the genetic algorithm (GA) is used for parameter optimization to obtain the optimal simulation parameters of the downburst. The process of simulation parameter optimization requires several iterations of solution, and each iteration of parameter optimization requires numerical simulation, which seriously affects the optimization efficiency. To this end, a surrogate model is introduced to participate in the optimization of simulation parameters instead of numerical simulation. The surrogate model is constructed by first determining the parameters to be optimized through sensitivity analysis, then conducting experimental design and numerical simulation to form the training data set, and finally constructing the Kriging surrogate model. The main computational consumption for building the proxy model is the use of numerical simulations to form the training data set. It should be noted that the numerical model can be computed in parallel once the experimental design scheme is determined.

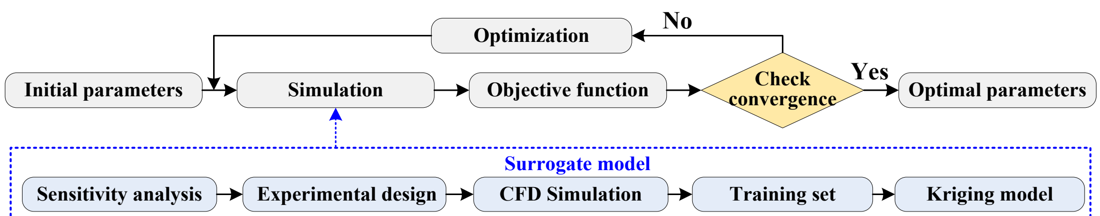
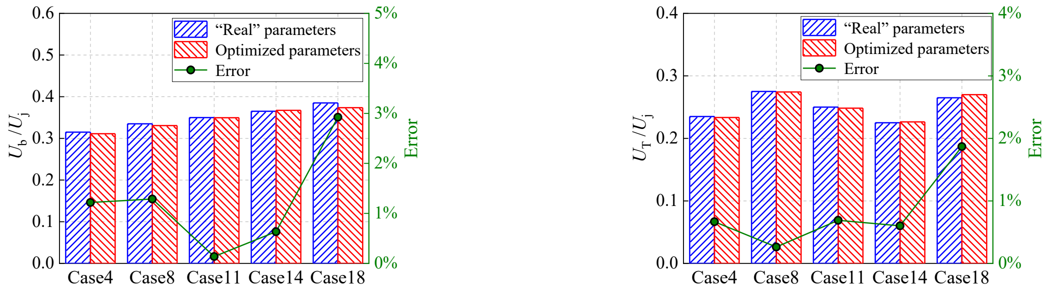


Fig.3 Flowchart of Parameter Optimization Process

3.2. Verification

To verify the reliability of the parameter optimization method established in this paper, a hypothetical downburst would be simulated numerically using a set of "real" parameters, including jet velocity U_j, moving velocity U_T and ambient wind speed U_b. The simulated characteristic parameters (peak wind speed value U_i, and time instant for peak value occurred t_i) of downburst wind speed are selected as the criteria to verify the accuracy of surrogate model, and the accuracy of Kriging model is tested by analyzing the error between the prediction results of Kriging model and the numerical simulation results (target values). Meanwhile, the optimized simulation parameters are obtained according to the optimization method established in this paper, and the accuracy of the parameter optimization algorithm is checked by comparing the optimized parameters with the "real" parameters. To demonstrate the reliability of the developed Kriging model the parameter optimization verification is repeated five times. For each verification, 20 sets of cases are used as the training set for building the surrogate model, and the remaining set is selected for test. Figure 4 shows the comparison results of the optimized simulation parameters and the "real" simulation parameters. It can be seen that the optimized simulation parameters are basically consistent with the "real" simulation parameters. The maximum errors of the U_b and U_T are respectively less than 3% and 2% in the five verification results. It can be considered that the accuracy of the algorithm established in this study meets the requirements.

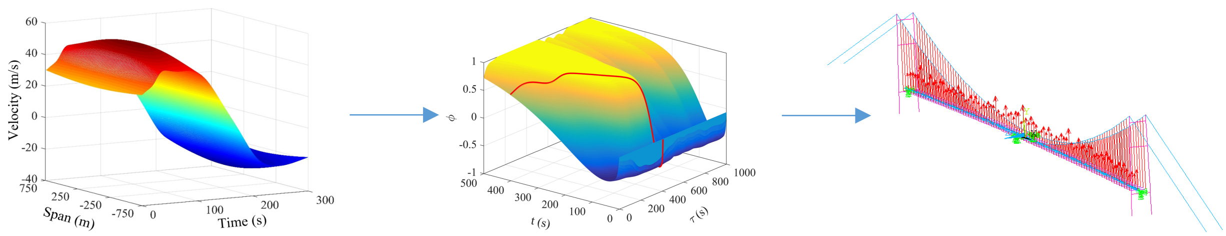


(a) Optimization results of U_b (b) Optimization results of U_T

Fig.4 Simulation Results using Parameter Optimization

4. BRIDGE RESPONSE UNDER DOWNBURST

As shown in Fig. 5, analysis of downburst-induced long-span bridge response is achieved by coupling of CFD-based moving downburst wind with Kriging model introduced for parameter optimization and computational structural dynamics (CSD)-based structural response with 2D indicial response function used for transient aerodynamics consideration.



(a) Moving downburst wind along bridge span (b) 2D indicial response function (c) CSD-based FE model with wind load

Fig.5 Analysis of bridge response under downburst wind

5. CONCLUSIONS

In this study, the downburst simulation parameters optimized based on Kriging surrogate model. In the process of parameter optimization, the surrogate model was introduced instead of the numerical model to participate in the optimization iteration, which greatly improved the efficiency of parameter optimization. The high accuracy of the optimized parameters is verified by five sets of test cases suggested that the surrogate model is a viable method to achieve high fidelity simulation of moving downburst. The CFD numerical simulation of downburst flow based on the optimal parameters was greatly improved. The significant contribution of the transient aerodynamics to downburst-induced bridge response has been highlighted.

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